LONGITUDINAL SURFACE PROFILES OF AN AIRPORT RUNWAY AND AIRCRAFT MOTION

By:
Katsura ENDO
Graduate School of Science and Engineering, Chuo University

Kenji HIMENO
Department of Civil Engineering, Chuo University

Akira KAWAMURA
Department of Civil Engineering, Kitami Institute of Technology

Yoshitaka HACHIYA
National Institute for Land and Infrastructure Management
Ministry of Land, Infrastructure and Transport

Kunihito MATSUI
Department of Civil Engineering, College of Science and Engineering,
Tokyo Denki University

PRESENTED FOR THE 2002 FEDERAL AVIATION ADMINISTRATION AIRPORT TECHNOLOGY TRANSFER CONFERENCE

05/02

LONGITUDINAL SURFACE PROFILES OF AN AIRPORT RUNWAY AND AIRCRAFT MOTION

By Katsura ENDO[1], Kenji HIMENO[2], Akira KAWAMURA[3], Yoshitaka HACHIYA[4] and Kunihito MATSUI[5]

ABSTRACT

Measurements of longitudinal profiles of pavement surfaces profilometer covering comparatively short length of highway pavements have been conducted by several research workers using non-contact type. However, there has been very few data on airport runways obtained for the whole length by careful measurement, since it is difficult to block off the airport traffic, and also, there have been no appropriate tools to measure surface profiles for several kilometers accurately within limited time.

In the former technical papers, the authors reported that longitudinal profile measurements were carried out on an actual runway of a principal airport near Osaka in Japan using a newly developed non-contact type profilometer. The profilometer was mounted in a vehicle and combined with Global Positioning System (GPS). It was capable of acquiring a profile of the pavement surface at intervals of 10mm with accuracy of ±1.2mm for short wavelength at normal vehicle speed.

Recently, the authors have made another profile measurements on an airport runway near Tokyo using the identical profilometer. Also, they obtained some acceleration data at the center of gravity of a Boeing 747 aircraft actually measured when taking off.

The measure profile data are analyzed using various tools, such as spectral analysis, wavelet analysis, and others. In addition, a computer simulation of a large sized aircraft responding to the measured runway profile has been carried out to simulate a taking off motion of the aircraft. The vertical accelerations at the center of gravity of the aircraft were computed, and compared with the measured ones. Finally, the aircraft's comfort, influence on the crew, influence on the body of the aircraft, influence on the pavement, etc. are analyzed.

1. INTRODUCTION

Some research workers have conducted measurements of longitudinal profile of the pavement surface using non-contact type profilometer. Such profile measurements have been mainly applied for highway pavements. The surface conditions have been analyzed from the viewpoint of ride comfort [1][2][3]. There has been few data obtained on airport runways by careful measurements, because it is difficult to cut off the airport traffic and there were not appropriate tools to measure runway surface profiles accurately for several kilometers long within a very limited period. However the authors had runway pavement profiles using a newly

[1] Doctoral Course Student, Graduate School of Science and Engineering, Chuo University, 1-13-27, Kasuga, Bunkyo-ku, Tokyo, 112-8551, Japan, E-mail: endo@civil.chuo-u.ac.jp

[2] Professor, Department of Civil Engineering, Chuo University, E-mail: himeno@civil.chuo-u.ac.jp

[3] Associate Professor, Department of Civil Engineering, Kitami Institute of Technology, 165, Koen-cho, Kitami, Hokkaido, 090-8507, Japan, E-mail: kawamura@stce2.civil.kitami-it.ac.jp

[4] Chief, Airport Facilities Laboratory, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport, 3-1-1, Nagase, Yokosuka, Kanagawa, 239-0826, Japan, E-mail: hachiya-y92y2@ysk.nilim.go.jp

[5] Professor, Department of Civil Engineering, College of Science and Engineering, Tokyo Denki University, Hatoyama-cho, Hiki-gun, Saitama, 350-0394, Japan, E-mail: matsui@g.dendai.ac.jp

developed non-contact type profilometer at a principal airport near Osaka in Japan [4][5].

It seems that airport runways have different characteristics of surface profile from highways. Studying the relation between the measured profiles and calculated accelerations will allow runway roughness, the aircraft's comfort and its influences on the crew, body of the aircraft and the pavement distresses to be evaluated, when the runway profiles are accurately measured.

Absolute profiles of a runway were accurately measured at one of the largest airport in Japan. Then several analyses were carried out to the profiles including the power spectrum density (PSD) analysis, simulation of aircraft movement, wavelet analysis and so forth.

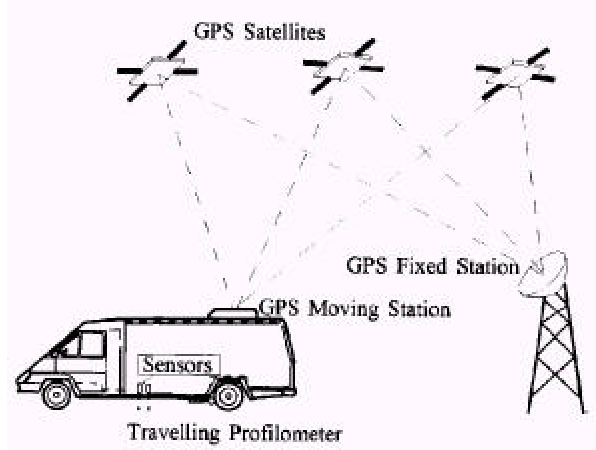

Figure 1. Schematic Diagram of Measuring System for Absolute Elevation

This study consists of three major parts. First, absolute profiles of runway pavement measured by non-contact type laser profilometer with the Global Positioning System are discussed. This combined system enables measuring the long wavelength of runway surface as well as the short one.

Second, evaluations of roughness and comfort level are discussed. These evaluations are based upon the discussed runway profiles above.

And finally, wavelet analysis is carried out to decompose the measured profiles into lots of waves that have different wavelengths. Then aircraft vertical movements are simulated using simulation software to know which wavelength affects the ride comfort of aircraft more.

1.1. Measurement Equipment

The profilometer used in this study is a non-contact type and employs the sequential two points method [6] to measure the profile. The response frequency of the laser distance meter is 4kHz that covers 144km per hour when the measurement interval is 10mm. It is possible to catch short wavelength range down to 1mm, on the other hand it is impossible to catch long wavelength range with this measuring equipment, because the error is accumulated and considerable distortion is unavoidable in long wavelength. To obtaining profile data that is accurate in both short and long wavelengths, GPS has been combined with profilometer in this study.

The point positioning GPS have often been used for satellite navigation systems without the fixed station and has an accuracy of 30m or more. The accuracy of 30m is not enough, therefore the real time kinematics type GPS has used in this study. The GPS has an accuracy of 2-3cm in the vertical direction. That system allows obtaining 1 elevation date a second. Obtained data are processed in real time mode during measurements. Figure 1 shows the system in schematically.

1.2. Measurement of Absolute Elevation

Measurement of runway profile at an airport near Tokyo, one of the largest airport in Japan, was conducted February 5 through 6, 2001.

Runway profile data was obtained on seven lines, 3,000m long each. The configuration is shown in Figure 2. They are the centerline and two lines 1.92m, two lines 4.65m, and two lines 5.50m away from the centerline, respectively.

The lateral positions of these lines were determined from the tires configuration pattern of

B747 aircraft as shown in Figure 3 [7]. Profile measurement carried out all the lines above with both directions, starting from the R34 side to the L16 side and starting from the L16 to the R34. The measurement speed at that time was about 50km/h for all the lines.

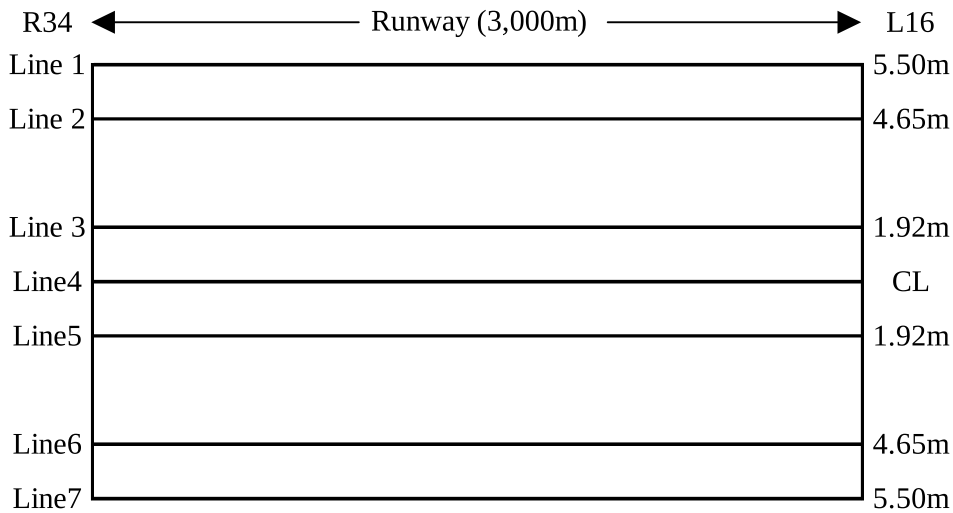

Figure 2. Configuration of Measurement Lines Along the Runway

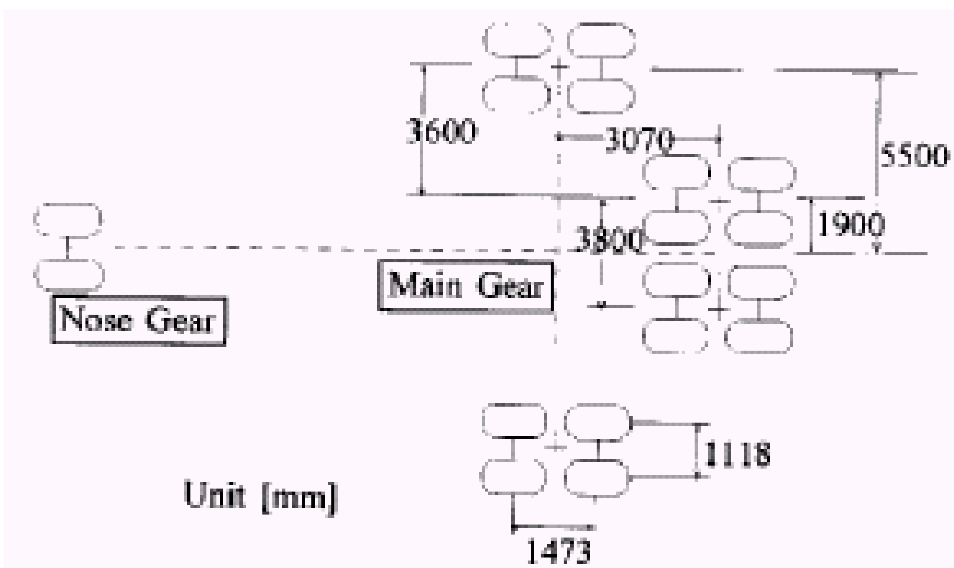

Figure 3. Tire Configuration Pattern of B747

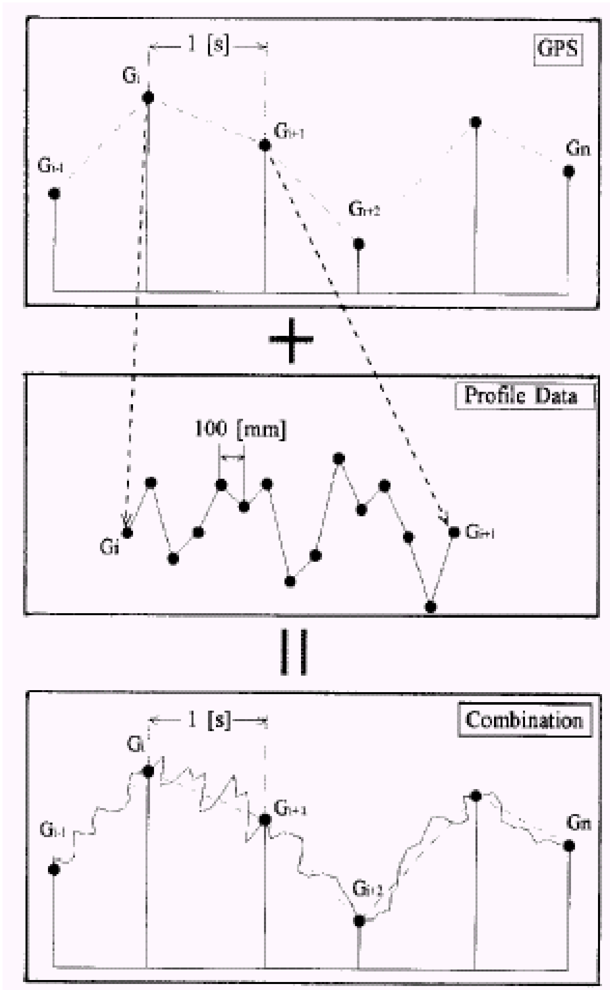

Figure 4. Obtaining Absolute Elevation Combining Profile Data and GPS

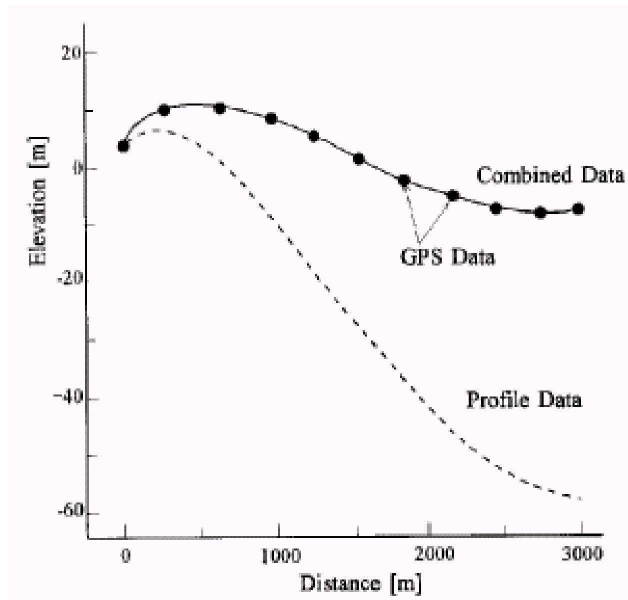

Figure 5. Combination of Profile Data and GPS Data

2. RESULTS OF RUNWAY PROFILE MEASUREMENTS

Surface elevations of the runway pavement were determined by measuring the range of long wavelength using GPS and the range of short wavelength using non-contact type profilometer as shown in Figures 4 and 5. Absolute vertical profiles were accurately obtained by combining these two data for considerably long distance as long as 3,000m.

The data are converted to space domain and combined with short wavelength data by profilometer, since long wavelength data are obtained every one second by GPS in time domain.

An example of measured absolute vertical elevation is shown in Figure 6. It is obvious that both the profiles that measurement starts from both sides (R34 and L16) are completely consistent. The standard deviation of its error is as little as zero.

3. POWER SPECTRUM DENSITY ANALYSIS

Power Spectrum Density (PSD) was employed to evaluate the evenness of the runway pavement surface. Maximum Entropy Method (MEM) was used for PSD calculation in this study. Runway profiles measured at interval of 1cm along 3,000m included extremely wide scope of wavelength range. It would be difficult to interpret the results, if a PSD analysis was

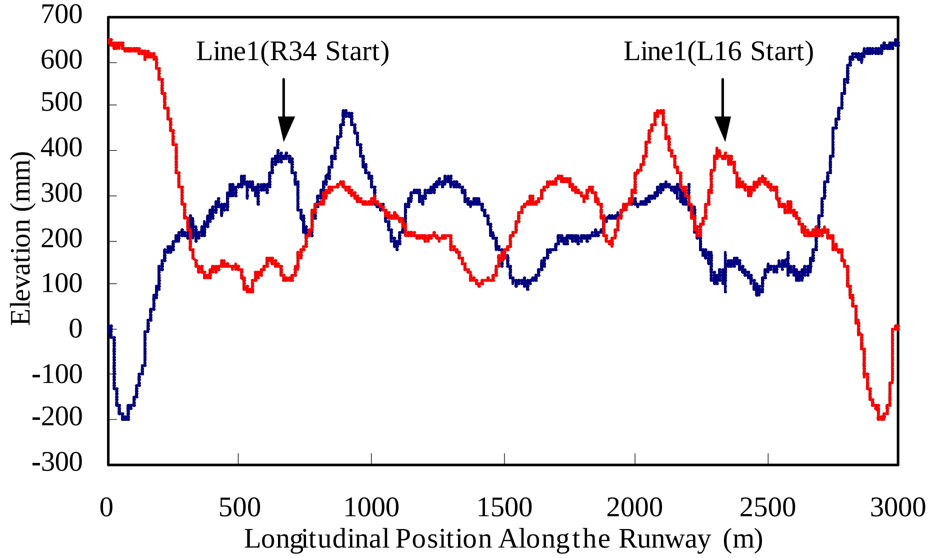

Figure 6. An Example of Measured Absolute Elevation

made using all these profiles at once. Thus analyses were carried out for the long and short ranges of wavelength.

The German Engineer Association (VDI) standard originally developed for the highway surface evaluations was adopted here as an index to compare the two analyses results as there were no evaluation standards found that were appropriate for runway pavement surface. Equation 1 and Table 1 shows the formula and coefficient, respectively:

$$S(\Omega)=S(\Omega_0)\left(\frac{\Omega}{\Omega_0}\right)^{-w} \qquad \text{Equation 1}$$

Table 1. Evaluation Standard of VDI for Highway Pavement Surface

Evaluation	$S(O_0)$ ($*10^{-6}m^2/c/m$)	?
Very Good	1.3	2.2
Good	6	2.18
Poor	22	2.18

where

S(O): power spectral density function of runway profile
O: spatial angular frequency (cm)
O_0: reference spatial angular frequency (=1cm).

3.1. PSD in Long Wavelength Range

Figure 7 shows an example of calculated PSD of 3,000m long measured line1. PSD is almost below ‘very good’ line. There was a very small difference in the calculated PSD among different measured lines. This is because the PSD is more affected by the long wavelength rather than local roughness or small distresses.

3.2. PSD in Short Wavelength Range

Each measured line was divided into 30 sections, each section was 100m long, to evaluate the local PSD conditions. Two examples of the results are shown in Figure 8 and 9.

As shown in Figure 8, PSD around the end of runway shows higher value than others and PSD are almost between ‘good’ and ‘very good’ lines. This end of runway is the target point of aircraft landing, so this will come from the impact load.

On the other hand, as shown in Figure 9, PSD around 1/3 of whole runway shows small value. In this case wave number of below 0.1 c/m shows extremely small value. Aircraft run at medium taxing speed at this point, then little impact load and little stationary load applied. This will cause small PSD values.

4. SIMULATION OF AIRCRAFT VERTICAL MOVEMENT

The runway profile is extremely important in maintaining safety and comfort of the aircraft at the time of takeoff, landing or taxiing. It is necessary for airport facility administrators to take into considerations the durability of runway pavement, operation cost and so forth, when making maintenance & rehabilitation (M&R) plan for runway pavement. Also it is necessary to monitor the long wavelength conditions regularly, because aircraft must move at a very high speed on the runway unlike the situation of highways.

Considerable improvement for the M&R plan has been made recently with research and development of Pavement Management Systems (PMS) for public highways. For evaluation of the level of unevenness affecting the ride quality of the vehicle, they have been vigorously developed with proposing many indices using mathematical model of the automobile. On the contrary, pavement evaluation methods for aircraft ground operation have not been reached to the point to develop an index that could directly connect to the runway M&R plan.

An aircraft movement simulations on the runway at takeoff and landing were carried out in this paper, having in mind that an index to evaluate evenness of pavement is ultimately proposed in relation to the airport pavement management plan. The APRas, that is one of the commercial aircraft simulation software, is adopted here to simulate aircraft vertical movement.

When retrieving a profile data, that simulation software is able to calculate the aircraft accelerations at the pilot's station (PSA) and the center of gravity (CGA). Evaluation at the pilot's station is very important when considering riding quality and pavement roughness [9]. Class of aircraft, simulation starting point, headwind, air temperature and so forth can be variable.

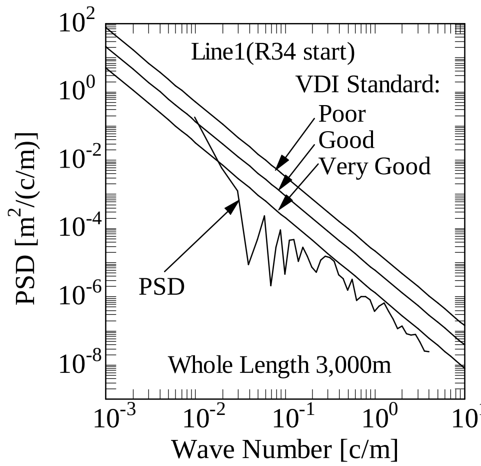

Figure 7. PSD for the Whole Length of Runway at Line1

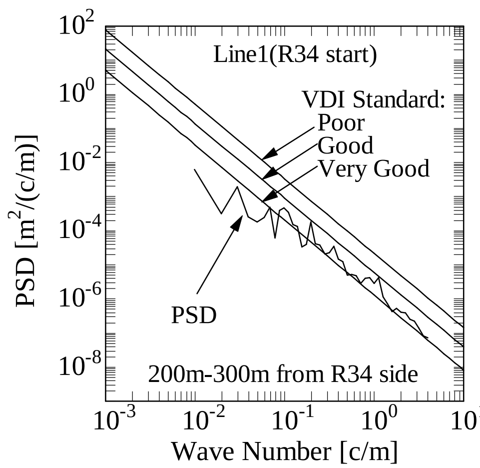

Figure 8. PSD for a 100m Section (at 200m-300m from R34 side)

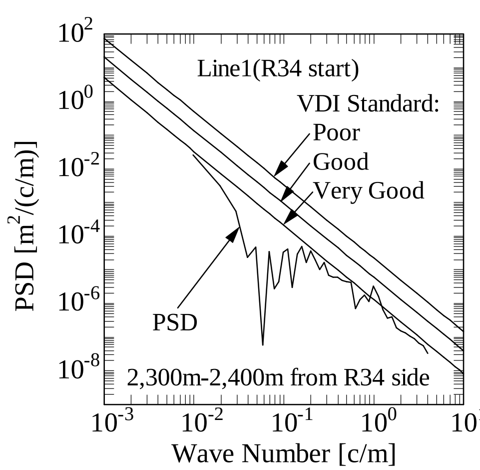

Figure 9. PSD for a 100m Section (at 2,300m-2,400m from R34 side)

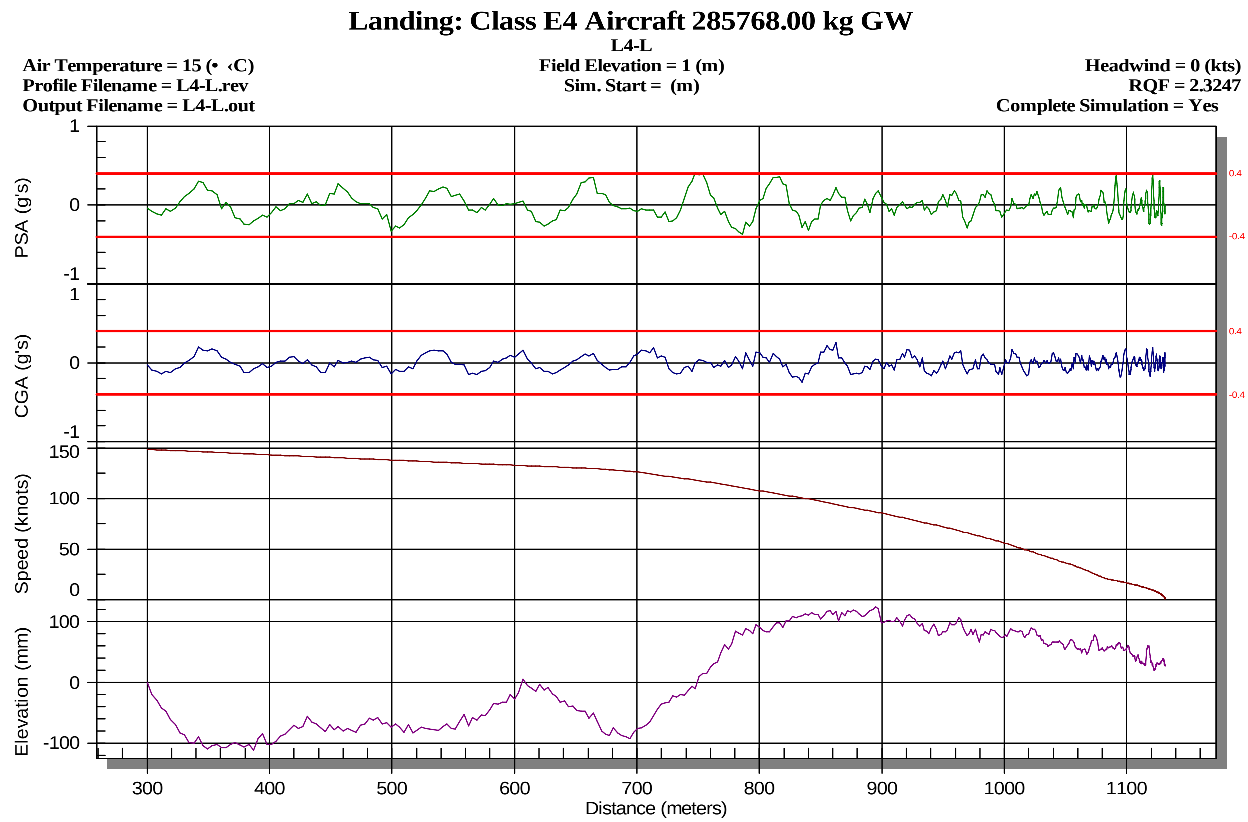

Figure 10. Simulated Aircraft Acceleration When Landing from Left Side of Runway on Line 4

4.1. Simulated Aircraft Accelerations

Two examples of simulated aircraft acceleration on the centerline (i.e. line4 in Figure 2) at the pilot's station and the center of gravity are shown in Figure 10 and 11. The simulated aircraft speed and the relative elevation (i.e. elevation at starting point is zero) are shown simultaneously. The former is the result of landing from left side of runway, and the later is the result of takeoff from left side of runway. Profiles measured from left side of runway were used for both cases.

When landing, the amplitude of aircraft acceleration is suddenly decreased and the frequency is short at the speed of 100 knots, on the other hand, the amplitude of acceleration shows the maximum and the frequency is long at the speed of 50-100 knots. It is seems that vertical acceleration is more effected by the aircraft speed than the runway profile in this case.

4.2. Wavelet Analysis of Runway Profiles

Wavelet analysis was carried out for measured runway profiles to know which wavelength affected to the ride comfort of aircraft more, while that analysis had applied to evaluate pavement roughness [8]. Wavelet analysis generally allows time-frequency signal analysis.

Original profiles were decomposed as an approximation wave and a detail one. Also a detail was decomposed as an approximation and another detail. Such process is called as wavelet transform. Daubechies4 (Db4) was adopted as the mother wavelet in this study. Then a runway profile was decomposed as:

$$S = D_1 + D_2 + D_3 + D_4 + D_5 + D_6 + D_7 + D_8 + D_9 + D_{10} + a_{10} \qquad \text{Equation (2)}$$

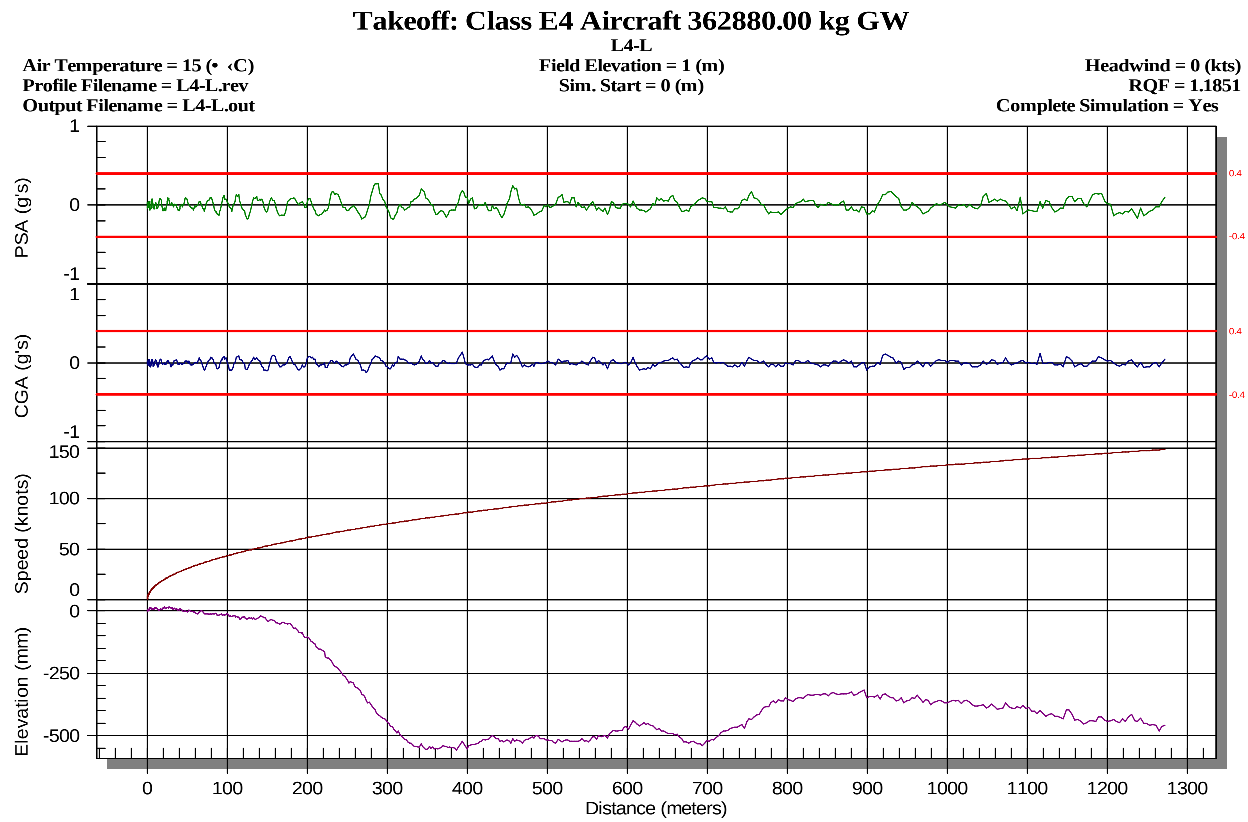

Figure 11. Simulated Aircraft Acceleration When Takeoff from Left Side of Runway on Line 4

where S is the original runway profile, D_n (n=1, 2, 3, … , 10) are details at level n, and a_{10} is the approximation at level 10. Wavelength at each level in this study is listed in Table 2.

4.3. Composing Virtual Runway Profiles

Virtual runway profiles were composed using original runway profile and decomposed wave as:

$$VS_n = S - D_n \qquad \text{Equation (3)}$$

where VS_n is nth virtual runway profile, S is an original profile and D_n (n=1, 2, 3, … , 10) are details at level n. Then totally ten virtual runway profiles were composed from one original profile.

Table 2. Wavelength at Each Level

Level	Wavelength (m)
D_1	0.4
D_2	0.8
D_3	1.6
D_4	3.2
D_5	6.4
D_6	12.8
D_7	25.6
D_8	51.2
D_9	102.4
D_{10}	204.8

4.4. Aircraft Simulation on Virtual Runway Profiles

Similar simulation to calculate aircraft vertical accelerations were carried out using the above virtual runway profiles. The Ride Quality Factor (RQF) was calculated to indicate ride quality of aircraft. The RQF provides a single, overall measure of the ride quality for the entire simulation. It is based on the calculated route means square (RMS) value of the pilot's station and aircraft's center of gravity. Higher RQF means worse ride quality [10].

Some examples of RQF calculation results for takeoff are shown in Figure 12 through 15. In Figure12, comparing to the result using original profile (bold line), decomposing short wavelength, e.g. D_1, affected neither increasing nor decreasing the Ride Quality Factors (RQF). On the other hand, decomposing longer wavelength, e.g. D_9, lowered the RQF values. It is found the tendency that longer wavelength (51.2m and more) lowers RQF, i.e. longer wavelength can improve ride comfort in this case.

Another example for takeoff was shown in Figure 13. Similar tendency was found that the shorter wavelengths affected to RQF values less and longer wavelength, e.g. D_7 and D_8, decrease the RQF values. On the other hand, D_9 and D_{10} increase the RQF values in this case.

Judging from these results, longer wavelength affect ride comfort of aircraft.

Figure 14 shows the simulation results for landing. In this case, shorter wavelength affects neither decreasing nor increasing the RQF values. The tendency that D_7 and D_8 decrease the RQF values and D_9 and D_{10} increase the RQF was similar to the case of takeoff (L16 start). In this case, the longest wavelength, D_{10}, is crucial to ride comfort.

Figure 15 shows another result for landing. RQF calculated from the original profile is very small. Decomposing the long wavelength makes RQF large.

These differences will come from actual landing or takeoff frequency on the runway.

5. CONCLUSION

Runway pavement profiles were measured by non-contact type profilometer at an airport near Tokyo. When the runway profiles were measured, a considerable amount of unevenness in frequency was discovered that might be the footprint of aircraft tires. From PSD analysis with divided sections, this will make PSD value higher especially at the point of takeoff on runway.

Aircraft vertical movement was simulated using the APRas software. Then vibration acceleration affecting the body at the pilot's station and the center of gravity of the B747 aircraft were calculated. It was found that aircraft speed was

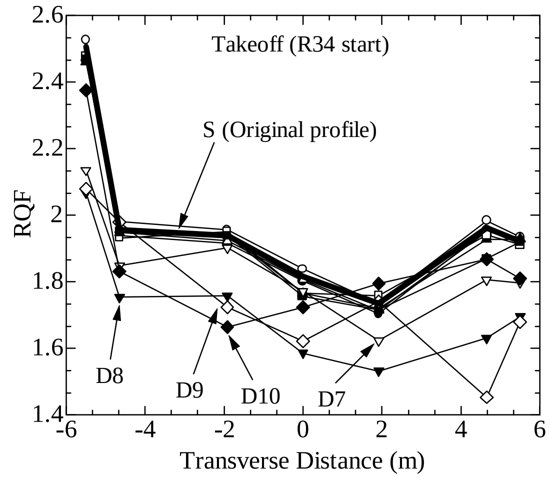

Figure 12. Transverse Distance vs. RQF (Takeoff, R34 Start)

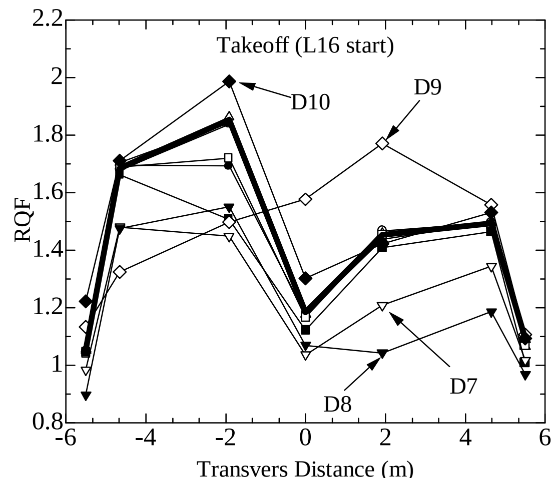

Figure 13. Transverse Distance vs. RQF (Takeoff, L16 Start)

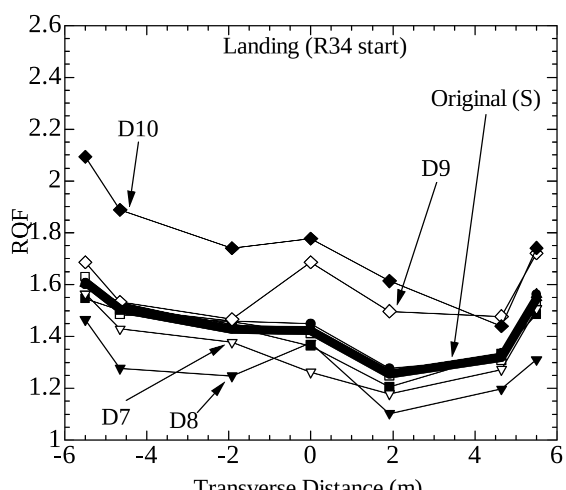

Figure 14. Transverse Distance vs. RQF (Landing, R34 Start)

more effective to its vertical acceleration than runway profile.

Wavelet analysis was carried out to show which wavelength was more effective to ride comfort of pilots or passengers. The RQF was selected to indicate the ride comfort in this study. It was found that longer wavelengths, e.g. more then 51.2m and more, were very effective in increasing or decreasing the RQF values for takeoff. This tendency was different from the directions of takeoff. Similar analysis was carried out for landing. It was found that longer wavelengths, e.g. 51.2m or more, were effective to changing the RQF values, too. Also the tendency depended upon landing directions.

Thinking about maintenance of runway pavement, those results will be important. Finding a wavelength affects to ride comfort helps airport authority to support making maintenance decisions.

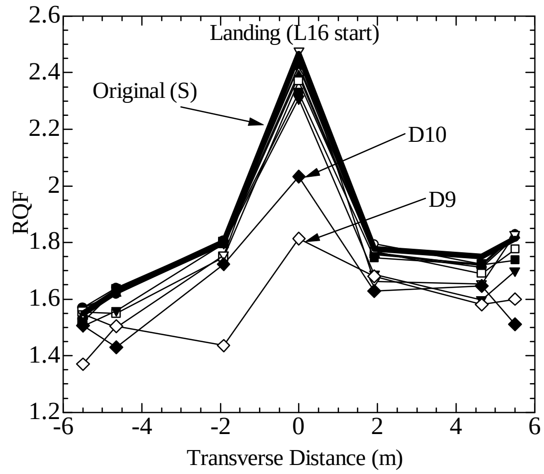

Figure 15. Transverse Distance vs. RQF (Landing, L16 Start)

ACKNOWLEDGEMENT

This study was supported by the Program for Promoting Fundamental Transport Technology Research from the Corporation for Advanced Transport & Technology (CATT).

ACRONYM

CGA:	Acceleration at the Center of Gravity
GPS:	Global Positioning System
MEM:	Maximum Entropy Method
PMS:	Pavement Management System
PSA:	Acceleration at the Pilot's Station
PSD:	Power Spectrum Density
RMS:	Route Means Square
RQF:	Ride Quality Factor
M&R:	Maintenance and Rehabilitation

REFERENCES

[1] Ichihashi, S., Fukuhara, T., Himeno, K., Kawamura, A. and Kasahara, A.: Development of a New Data Acquisition System for Measuring Pavement Surface Profile, Proceedings. the 2nd International Symposium on Pavement Surface Characteristics of Roads and Airfields, Berlin, pp.309-324, Jun., 1992

[2] Kawamura, A., Himeno, K., Ogawa, S., Kuriyagawa, Y. and Ichihashi, S.: Some New Approaches to Evaluation of Road Surfaces, Procs. 6th Conference on Asphalt Pavements for Southern Africa, Cape Town, Vol.2, pp.IV_110 - IV_118, Oct., 1994

[3] Kawamura, A., Himeno, K., Kasahara, A., Shibazaki, R. and Kameyama, S.: Some Considerations on the Measurement and Evaluation of Road Roughness, International Journal of Vehicle Design, Vol. 3, No.I-4, pp.261-274, 1996

[4] Akimoto, T., Kawamura, A., Himeno, K. and Kasahara, A.: Characteristics of Pavement

Surface Profile on Airport Runways, Procedings of the 3rd International Symposium on Pavement Surface Characteristics of Roads and Airfields, Christchurch, pp.171-187, Sep., 1996

[5] Himeno, K., Kawamura, A. Kasahara, A. and Nishizawa, T.: Characteristics of Surface Profiles of an Airport Runway Pavement, Preprint of TRB 79th Annual Meeting, Washington D.C., Jan., 2000

[6] Tozawa, K., Sato, H. and O-hori, M.: A New Method for the Measurement of the Straightness of Machine Tools and Machined Work, 1981.

[7] Kawamura, A., Shimeno, S., Himeno, K., Komatsubara, A. and Hagiwara, T.: Study on Application of the Multire solution Analysis to Road Profile Evaluation, Proceedings. 3rd International Symposium on the Environmental Impact of Road Unevenness, Porto, pp.121-132, Mar., 1999

[8] Oguri, N. Himeno, K., Kawamura, A. and Nakamura, R.: Application of Wavelet Analysis on Evaluation of Roughness of Pavement Surfaces, Proceedings. 4th International Symposium on Pavement Surface Characteristics of Roads and Airfields, Nantes, pp.57-66, May, 2000

[9] Hachiya, Y., Yin, J., Takahashi, O. and Himeno, K.: Aircraft Response Based on Airport Pavement Roughness Evaluation, Journal of Materials, Concrete Structures and Pavements, JSCE, No.634/V-45, pp.403-411, Nov., 1999

[10] APR Consultants, Inc.: Airport Pavement Roughness Assessment Software Help, version 2.2.3.